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Full Length Article

The role of working memory capacity in implicit and explicit sequence learning of children: Differentiating movement speed and accuracy

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ABSTRACT

This study investigated the role of working memory capacity on implicit and explicit motor sequence learning in young children. To this end, a task was utilized that required a gross motor response (flexing the elbow) and that could differentiate between movement speed (i.e., reaction time and movement time) and movement accuracy. Children aged 7–9 years practiced a serial reaction time task that involved the production of a fixed sequence of elbow flexions of prescribed magnitude across two consecutive days. Children in the explicit group were informed about the presence of the sequence and were shown this sequence, while children in the implicit group were not made aware of the sequence. Additionally, children's verbal and visuospatial working memory capacity was assessed. Results of day 1 regarding movement speed revealed no evidence of sequence learning for either group, but movement accuracy results suggested that sequence learning occurred for the implicit group. For both groups, only improvements in movement accuracy were consolidated on day 2, indicating both general and sequence specific learning. Working memory capacity did not correlate with learning in either of the groups. Children in the explicit group accumulated more sequence knowledge compared to children in the implicit group, but this knowledge did not translate to more or better sequence learning. The minimal differences found between the implicit and explicit condition and the absence of a role for working memory capacity add to the increasing evidence that the observed differences between implicit and explicit sequence learning in adults may be less distinct in children.

1. Introduction

Adequate performance of motor skills is critical for everyday life, for example, getting dressed, riding a bike to school and playing outside. Not surprisingly, then, the investigation of the most effective methods to perform and learn motor skills has received considerable attention in the academic literature (e.g., Masters & Poolton, 2012; Wulf & Shea, 2002). For several decades cognitive

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scientists have typically categorised motor learning as either implicit or explicit. Implicit learning emerges when the learner is unaware of the learning that is taking place, that is, when they cannot verbalise what they have learnt or how they performed a movement. The opposite is true for explicit learning, in which learners build up a pool of declarative knowledge about the task and movement execution that they can consciously access and use in their performance. Skills acquired implicitly are more resilient to psychological and physiological stress, and more likely to be retained over time (see Masters & Poolton, 2012, for an overview). It has also been found that implicit learning is independent of age and cognitive resources (Meulemans, Van der Linden, & Perruchet, 1998; Reber, Walkenfeld, & Hernstadt, 1991). Consequently, implicit learning has been advocated as superior to explicit learning, especially for children (Masters, Kamp, & Capio, 2013).

To optimize motor learning, there is an increasing interest in factors that influence the effectiveness of different types of interventions or training methods. With regard to implicit and explicit learning, working memory (WM) capacity has often been mentioned as an important factor that may mediate learning (Buszard et al., 2017; Steenbergen, Van Der Kamp, Verneau, Jongbloed-Pereboom, & Masters, 2010). WM capacity refers to the ability to retain and manipulate information also in the face of distractions (Baddeley, 2000). Individuals typically differ in their ability to retain and manipulate verbal information compared to visuospatial information. Consequently, separate measures have been developed for assessing verbal and visuospatial WM capacity. Given that explicit learning is thought to be highly dependent on cognitive resources, such as WM (Maxwell, Masters, & Eves, 2003), researchers have proposed that WM capacity may constrain the ability to learn explicitly (Steenbergen et al., 2010). More specifically, given that feedback and instructions are often provided verbally, it is thought that verbal WM capacity is critical for explicit learning (Maxwell et al., 2003). Nonetheless, visuospatial WM capacity is also likely to be pertinent for improving motor performance given that feedback regarding movements in the environment is also often visual.

To study implicit and explicit learning, including the role of WM capacity, the most common paradigm within experimental psychology has been the serial reaction time (SRT) task. Typically, a finger tapping task is employed whereby participants learn a sequence of keys to tap as response to a stimulus that appears on the screen (Nissen & Bullemer, 1987). In these experiments, participants are exposed to a reoccurring fixed sequence over a number of practice blocks. Participants are either explicitly informed of the sequence (explicit learning) or are only instructed to perform the task as fast and accurate as possible without being instructed about the sequence (implicit learning). After a number of practice blocks, participants are exposed to a different sequence, or a set of random stimuli. If the sequence has been learnt, participants should display a decrease in performance (i.e., an increase in reaction time) for this new sequence. The difference in performance between the learnt sequence and the new sequence is the primary measure of sequence specific learning in this paradigm. Typically, studies using SRT-tasks mainly focus on movement speed rather than movement accuracy. Indeed, this is because SRT-tasks have a dichotomous outcome (i.e., correct or incorrect) with only a minimal number of incorrect responses. By contrast, Moisello and colleagues designed an SRT task which required a discrete reaching movement, allowing movement speed to be separated in reaction time (i.e., time needed to initiate the movement) and movement time (i.e., time between movement initiation and reaching the goal) (Moisello et al., 2009). They reported that sequence learning in adults was represented by improved reaction times, but not by changes in movement time, indicating that participants better anticipated the next trial in the sequence. In order to provide a task that is more representative for everyday life, it is important to also consider movement accuracy, as many of our goal-directed behaviour show trade-offs between speed and accuracy (see Elliott, Hansen, Mendoza, & Tremblay, 2004, for a theoretical framework; see also Verneau, van der Kamp, Savelsbergh, & de Looze, 2014). Consequently, in the current experiment, we move beyond the classical SRT tasks and follow the lead by Moisello et al. by including reaction time, movement time and movement accuracy in a new experimental setup.

The reported relationships between WM capacity and sequence learning are ambiguous. Studies have reported a relationship between *explicit* sequence learning and both visuospatial WM capacity (Bo & Seidler, 2009; Martini, Furtner, & Sachse, 2013) and verbal WM capacity (Unsworth & Engle, 2005), while other studies have reported a relationship between *implicit* sequence learning and both verbal WM capacity (Bo, Jennett, & Seidler, 2012; Howard & Howard, 1997) and visuospatial WM capacity (Bo, Jennett, & Seidler, 2011). In addition, studies have reported a lack of relationship between both components of WM capacity and either implicit or explicit sequence learning (Kaufman et al., 2010). Thus, based on the empirical data, the relationship between implicit and explicit learning, and WM capacity (either verbal or visuospatial) is ambiguous at best (Buszard & Masters, 2017; Janacsek & Nemeth, 2013, 2015). Furthermore, conclusions drawn from SRT studies sometimes mask the true results. For instance, some studies assume a relationship between WM capacity and sequence learning based on a measure that is typically viewed as an indicator of general task improvements rather than sequence learning (i.e., improvements in performance from the start of practice to the end of practice, rather than the difference between a learnt sequence and a new or random sequence) (Bo et al., 2011, 2012; Bo & Seidler, 2009). Also, studies often assume learning based on performance during one day, thereby neglecting consolidation, or retention, as a defining feature of learning. Finally, as already mentioned above, most SRT studies only consider learning based on improvements in reaction (or movement) time and do not consider movement time and accuracy, thereby neglecting an important aspect of human motor performance.

All of the above-mentioned studies examined the relationship between WM capacity and sequence learning in healthy adults. However, the fundamentals of most of our everyday motor behaviour are learnt during childhood. During these years, cognitive capacities, such as WM, are continuously developing and they do not reach their full capacity until adolescence (Gathercole, Pickering, Ambridge, & Wearing, 2004). Surprisingly, however, the number of studies using SRT tasks in children is limited. Nevertheless, they do show that children can learn this task in an implicit condition (Gofer-Levi, Silberg, Brezner, & Vakil, 2013; Meulemans et al., 1998; Thomas & Nelson, 2001; Wilson, Maruff, & Lum, 2003). However, the proposed superior performance over explicit learning was either not studied (Gofer-Levi et al., 2013; Meulemans et al., 1998; Wilson et al., 2003) or not found (Thomas & Nelson, 2001). In the only study to our knowledge that investigated the role of WM capacity in an SRT paradigm in children, visuospatial WM capacity was unrelated to learning in both the implicit and explicit practice condition (Jongbloed-Pereboom, Janssen, Steiner, Steenbergen, & Nijhuis-van der Sanden, 2017). However, larger visuospatial WM capacity was related to better overall performance during practice in both conditions, highlighting a difference between learning and practice (also see van Abswoude, van der Kamp, & Steenbergen, 2018). It must be acknowledged that this study did not measure verbal WM capacity. Combined, these studies question the proposed benefit of implicit learning over explicit learning and the role of WM capacity for children in an SRT task.

The aim of the current study was to extend previous research by examining the role of both verbal and visuospatial WM capacity on sequence specific performance improvements in an implicit and explicit SRT task in children. Previous studies have shown that children can learn motor (sequence) tasks following both implicit and explicit methods (Masters et al., 2013; Thomas & Nelson, 2001). In addition, because WM capacity is still developing in children it has been suggested that relations between explicit motor learning and WM capacity, if any, are likely to be more pronounced in children than in adults (Steenbergen et al., 2010). Therefore, children are an important population to further assess the role of WM capacity in implicit and explicit sequence learning. A significant correlation between WM capacity and performance improvements will be taken as evidence for a role of WM capacity in motor learning. We developed a task in which children were able to improve on both the temporal and spatial dimension, operationalized via reaction time, movement time and accuracy outcome measures. As a secondary aim we also assessed consolidation of these general and sequence specific improvements the following day (i.e. learning). A verbal recall test on the second day was used to determine the amount of sequence knowledge of the children.

2. Methods

2.1. Participants

A sample of 24 children (sample size based on the study of Thomas and Nelson (2001)) aged between 7 and 9 years ($M = 9.2$, $SD = 0.6$) participated in the study. Children were recruited from a mainstream primary school. All parents and children provided written informed consent. The procedures of the study were approved by a local ethics committee.

2.2. Apparatus and materials

2.2.1. Experimental task

The motor sequencing task was based on serial reaction time tasks, whereby participants respond to stimuli on a computer screen as quickly as possible by pressing a corresponding key on a keyboard. Our motor task replaced keyboard pressing with a more gross motor skill – flexing the elbow to various degrees, to allow a continuous measure for both movement time and accuracy (see Fig. 1).

Participants sat in a chair and held a straight handle with their preferred arm. The length of the lever that the handle was attached to was adjustable between 19 cm and 23 cm. We adjusted the lever length so that it matched the length of the participants arm. Participants were instructed that their arm should rest comfortably on the table next to the apparatus. The height of the participants chair was adjusted to better facilitate correct and comfortable positioning. The task required participants to flex their elbow so that the lever moved to the target angle as presented on an *angle display screen* (not to be confused for the computer screen; see Fig. 1) as quickly as possible. Participants were then required to extend their elbow so that the lever returned to the starting position. The *angle display screen* was positioned directly in front of the participants at eye level. The target angles that were shown to participants varied between 10°, 30°, 50° and 70°. Angles appeared on the *angle display screen* via a preprogramed sequence stored on a microcontroller. A new angle was displayed on the screen at the beginning of each trial. A new trial began after a short rest time (i.e., 1100 ms, which is similar the study of Moisello et al., 2009, who also separated reaction time and movement time) with the handle having returned to 0° rest position. This process was automated and is outlined in Fig. 2. The HEDS-5500 Incremental Optical Encoder resolved small angle changes from the handle and arm pivot to the microcontroller which sent processed information containing trial tracking data for each trial regarding (a) reaction time, (b) movement end time, (c) total task time, and (d) movement accuracy. Time was reported in milliseconds. Movement accuracy was determined by cumulative discrete displacement counts over the participants drawn arc motion. Calibration of this apparatus prior to the experiment revealed that the mean error in movement accuracy was $0.2° \pm 0.3°$. After each practice block, the microcontroller sent the best trial time feedback to the *angle display screen* for the participant to see. This feedback was the fastest reaction time of that block and was used to encourage participants to not only be accurate but also be as fast as possible. Further feedback after each trial was provided to the participant via a duel LED bar indicator. A green light bar appeared above the *angle display screen* for an accurate trial within ± 5° of the target displayed angle while a red light appeared for an inaccurate trial beyond ± 5°. The red or green indication light remained lit above the *angle display screen* for the entire response-to-stimulus interval of approximately 1100 ms.

2.2.2. Working memory assessments

The capacity limits of visuo-spatial WM and verbal WM were determined with two tasks from the Automated Working Memory Assessment (Alloway, 2007): the Listening Recall Task and Spatial Recall Task. The tasks involved briefly remembering and manipulating verbal and visuospatial stimuli (i.e., visual patterns and words). Higher scores on the task represent larger capacities of WM. Test-retest reliability was shown to be high for both tasks in a sample of 128 participants aged 4 to 22 years (Listening Recall Task, $r = 0.88$; Spatial recall Task, $r = 0.79$; Alloway, 2007).

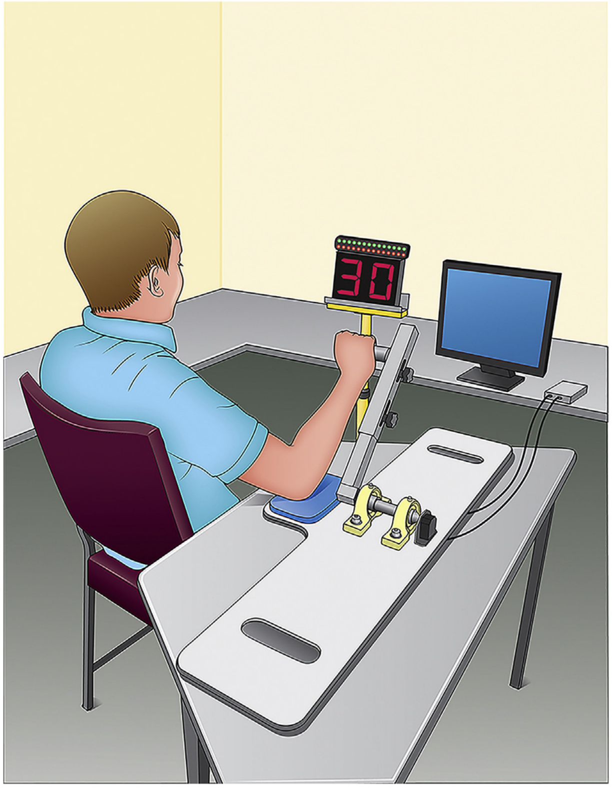

Fig. 1. The set-up of the experimental task. The goal for the participants was to raise the lever to the angle displayed on the *angle display screen* as quickly as possible. The computer screen presented the task instructions before each session and between each practice block. Participants received feedback regarding the accuracy of their movement via a green light (< ± 5°) or a red light (> ± 5°) that appeared on the *angle display screen* after every trial. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

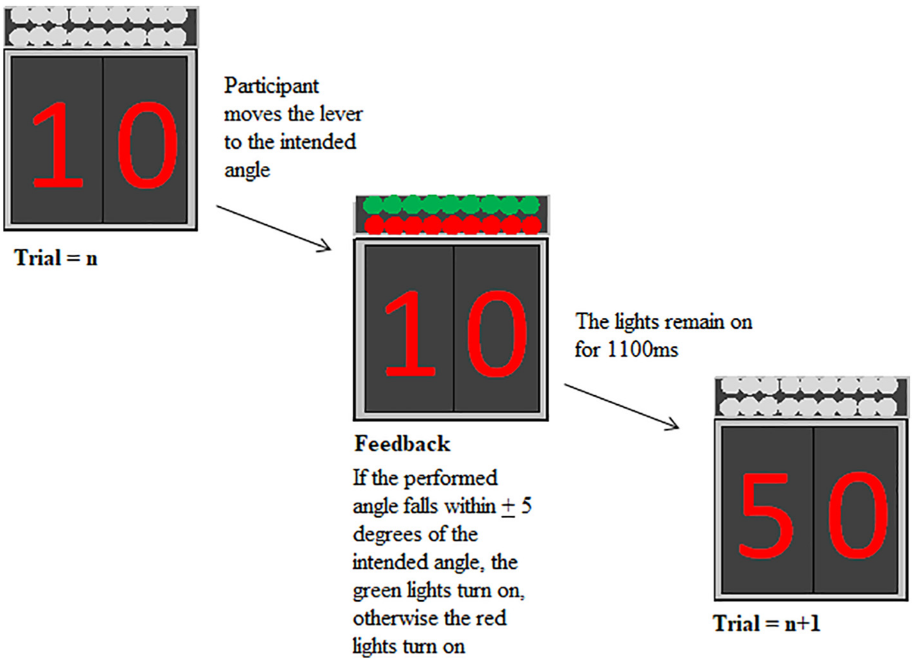

Fig. 2. Schematic representation of an experimental trial. The participant moves the lever to the intended angle and back down again (i.e., back to the starting position). When the lever returned to the starting position, the feedback light turned on for the complete response-stimulus interval.

2.3. Procedure

The experiment was conducted over two consecutive days. Participants were required to sit with a researcher in a quiet room for approximately 45 min on each day. At beginning of each day, all participants completed one WM capacity assessment. To ensure consistency across participants, the Listening Recall Task was completed on day 1 and the Spatial Recall Task was completed on day 2. Following each working memory task, participants were asked to move to a position ready to commence the motor sequencing task. Before the start of the experiment on day 1, the researcher randomly assigned the participant to a group by drawing a group name out of an envelope. Participants were either allocated to the implicit group or the explicit group. Implicit and explicit groups differed based on the information that was provided to the participants about the motor sequencing task, with only the explicit group being informed about the fixed sequence embedded in the task.

2.3.1. Day 1 – practice

A *computer screen* was positioned in front of the participant, which detailed the instructions of the task (see Appendix A). Participants were told that this is a game, and the primary aim of the game was to move the rod as fast as possible to the angle presented on the *angle display screen*. However, participants were also told that only correct trials would be recorded to encourage accurate performance. Participants underwent two blocks of eight familiarization trials. The first block of familiarization trials focused on movement accuracy. To ensure participants understood what each angle was, the researcher showed the participant a sheet of paper that illustrates 10°, 30°, 50° and 70°. Afterwards, with the participant holding the handle, the researcher moved the lever to each angle and held it there for approximately 5 s. This allowed participants to experience the required movement and posture for each angle. In the second familiarization block, the focus was on speed. Participants were told that this was the final practice before playing the game. During this block of trials, participants experienced the green/red light feedback. Participants were also notified that their fastest correct trial would be reported at the end of each block of trials. Hence, after the second familiarization block, a number appeared on the *angle screen,* which represented the fastest correct response time in seconds. A one-minute rest period was provided after the second familiarization block. Participants were encouraged to ask any final questions during this time.

The practice phase was based on a previous SRT study using a finger tapping task in children (Gheysen, Van Waelvelde, & Fias, 2011). The practice phase comprised of 10 blocks of 50 trials, with 1-min rest breaks between blocks (see Table 1). In blocks 1 through 8 and in block 10, the required angles followed a predetermined 10-item sequence with an identical structure as the sequence used by Gheysen et al. (2011) (i.e. 10°, 50°, 70°, 30°, 50°, 10°, 70°, 30°, 10°, 70°). This sequence was repeated five times per block. In block 9, the sequence was replaced by a new 10 item sequence, which was created by a simple transformation, $10^\circ < - > 70^\circ$(i.e. 70°, 50°, 10°, 30°, 50°, 70°, 10°, 30°, 70°, 10°). This new sequence was supposed to seem random to participants, while remaining the same number of occurrences of each angle within the sequence, both having only one reversal (10°, 70°, 10°), but also being maximally discriminative because there was no single triplet (any three subsequent numbers) that occurred in both sequences (see Jiménez, Vaquero, & Lupiáñez, 2006, for a similar procedure).

Participants in the implicit group were not informed on the repeating fixed sequence. Conversely, participants in the explicit group were told that the angles appear in the same order most of the time. Participants in this group were shown the sequence during the rest period between blocks on the computer screen and were instructed that knowing the order of the angles will help them achieve faster performance for each trial. They were also asked to focus on this sequence in the rest periods.

2.3.2. Day 2 – consolidation

The second day started with general instructions and two familiarization blocks; the first block was similar to the familiarization block on day 1, while the second was a practice block of the transfer test used in block 4. This transfer test changed the context of a task to a selection task which was performed to answer questions beyond the scope of this paper and is not reported here. Participants in the explicit group were then reminded of the fixed sequence in the same manner as day 1. Participants then performed five more blocks of 50 trials with a 1-min rest between blocks (see Table 1). Block 1 was a regular sequence block, but block 2 was used to assess the consolidation of the sequence specific improvements (note: only these first two blocks are reported in this paper). To this end, each 10 trials either followed the learnt (i.e., fixed) sequence or the new sequence. The new sequence was the same sequence as the random block on day 1 (see Jiménez et al., 2006, experiments 3 and 4, for a similar procedure). The first 10 trials followed the new sequence, then the fixed sequence, and so on. This resulted in 30 random trials and 20 learnt sequence trials.

Table 1
Representation of the design of the study.

	Day 1											Day 2						
Block	F1	1	2	3	4	5	6	7	8	9	10	F2	F3	11	12	13[a]	14[a]	15[a]
Type	F	S								R	S	F	F	S	C	S	T	S

Note. All blocks, apart from the familiarization blocks, included 50 trials. F = Familiarization block; S = Sequence block, consisting of five repetitions of the 10-item fixed sequence (i.e., 50 trials); R = random block, consisting of five repetitions of a new sequence (i.e., 50 trials); C = Consolidation block, consisting of two repetitions (i.e., 20 trials) belonging to the fixed sequence and three 3 repetitions (i.e., 30 trials) belonging to the new sequence. T = Transfer block, not reported in this paper.

[a] These blocks are not reported in this paper.

After the final block on day 2, participants' knowledge of the fixed sequence was assessed. Participants received a series of questions to address their explicit knowledge about the embedded sequence. Participants in the implicit condition were first asked if something about the task stood out to them. Next, they were told that there was a 10-item sequence embedded in the trials and were asked if they were aware of this sequence. If participants reported awareness of the sequence, they were asked to detail when exactly they noticed the sequence (i.e., during the practice or during/after the transfer tasks). Participants in the explicit condition were asked if they noticed the sequence when performing the task, whether they used the sequence information to improve task performance, and when they became aware of the sequence. The last question was similar for both groups and required participants to freely recall the sequence (see Lejeune, Catale, Willems, & Meulemans, 2013, for a similar procedure). For this task, participants were asked to write down what they thought the sequence was. Participants were given the first number followed by 20 empty boxes that represent the next 20 trials. Participants were asked to avoid repetitions. The number of correct triplets recalled was calculated. A high score on the task represents explicit sequence awareness (Destrebecqz & Cleeremans, 2001).

2.4. Data analysis

2.4.1. Dependent variables

2.4.1.1. Reaction time (RT). Reaction time was defined as the time between stimulus presentation and movement onset.

2.4.1.2. Movement time (MT). This was defined as the time between movement onset and the time at which the movement reached the maximum angle for that trial. Pilot testing showed that participants restrained their downward movement to prevent the handle from slamming down; hence we decided to remove the downward motion back to the starting position from the calculation of response time. Furthermore, only trials where the movement fell between $+/-\ 5^{\circ}$ of the intended angle were included in the analysis (i.e., correct trials). This is because response time is closely related to the distance of movement; hence, we only wish to assess movement time for movements of similar distance. Additionally, because movement time is dependent on the magnitude of the angle that needs to be produced, the index of difficulty was calculated for each angle based on Fitts law (Fitts, 1954) using the formula $ID = \log_2(2*TA)$,[1] in which ID is the index of difficulty and TA is the target angle. Movement times were multiplied by this ID to create comparable times for all angles.

2.4.1.3. Movement accuracy (Acc). This was defined as the absolute difference between the intended angle (i.e. the angle that appears on the computer screen) and the maximum angle of the participant's actual movement on that trial. A smaller difference represents better accuracy. All trials, also incorrect trials, were included.

2.4.1.4. Sequence knowledge. The number of correct triplets in the recall task was calculated. This number was compared against chance level, which was set on 5 (i.e., with 4 different angles, 36 triplets without repetition of angles could be generated; 10 of these triplets belonged to the fixed sequence, while 19 was the maximum number of correct triplets in the recall task; hence, chance performance was $19*10/36 = 5.2$). A score above 5 was considered an indication of sequence awareness (see Lejeune et al., 2013).

2.4.1.5. Phases in the experiment. Analysis of the data was performed for four different phases that exist in this experiment with their corresponding blocks:

1. General improvement: this includes block 1 and 8 and is included to check if children are able to improve on the task.
2. Sequence specific learning; this includes block 8 (fixed sequence) and 9 (new sequence).
3. Consolidation of general learning; this compares block 10 (final block day 1) and 11 (first block day 2).
4. Consolidation of sequence specific learning; this compares the fixed sequence trials to the new sequence trials within block 12

2.4.2. Data preparation

The data were first checked for missing values. There were 19 counts (0.1%) of missing data for each dependent variable of the sequencing task (response time & accuracy). This data was not missing at random, but was due to a technical issue. Data stopped recording for one participant (ID #4) during block 3 from trials 31 to 49. No imputation methods were applied to this missing data. Next, the data were checked for abnormalities. The following values were removed from the analysis:

- Working memory scores > 40 (40 represented the maximum score),
- The produced angle was smaller than 1 (typically represents an error in the task),
- The reaction time (time between presentation of the stimulus and the start of the movement) was smaller than 1 ms (typically represents a technical error),
- The reaction time was larger than 5000 ms (this occurred when the child was not focusing),
- The movement time was smaller than 1 ms (typically represents an error in the task).

[1] The complete formula for the index of difficulty is $ID = \log_2(2D/W)$ in which D represents the distance of a target and W represents the width of the target. In the current experiment the target is only defined by a distance (i.e. angle) which is why the width is deleted from the original formula.

2.4.3. Statistical analysis

The effect of condition and WM on speed and accuracy in each of the four phases of the experiment was analysed with a linear mixed-effect model approach, using the lme4 package (Bates, Mächler, Bolker, & Walker, 2015) in R studio (R Core Team, 2014). Mixed modelling was used instead of repeated measures ANOVA's because of differences in amount of trials that were included in analysis between participants. These differences were a consequence of only assessing correct trials. This approach also fits with the non-independence of the data in which each participant contributed multiple data points to each of the dependent variables. By using mixed-effect models, the variability of these scores was retained. Mixed models were initially applied to the raw (untransformed) data. However, residual plots showed that all models failed to conform to homoscedasticity. Greater variation was observed in the upper values for each dependent variable. Consequently, a square root transformation was applied to the data.[2] Data were transformed back to the original scale when reporting estimates.

The model setup was similar for all phases of the experiment. Factorial predictors (i.e. group and block) were coded using sum-to-zero contrasts. The models included a fixed intercept, a fixed effect for Group (with explicit coded as 1 and implicit coded as -1), a fixed effect of Time (i.e. blocks corresponding to the specific phase) and the interaction between these two factors. To analyse the effects of WM capacity, fixed effects of verbal WM capacity and visuospatial WM capacity were added in separate models. The repeated nature of the data were modelled by including a per-participant random intercept and a per-participant random slope of Time (i.e. change in performance over blocks for the specific phase) and the random correlation between the random slope and the random intercept. For the count outcome of the number of correct triplets recalled, the model family was a Poisson with a log link.

Statistical inferences about the fixed and random effects were based on a Likelihood Ratio Tests of the full model with the effect in question (i.e., the interaction between group and time) against the model without the effect in question, using R's ANOVA function. The likelihood ratio tests were performed with a Chi-square distribution using the appropriate degrees of freedom for the comparisons being made. Assessments about the magnitude of effects between groups were based on linear contrasts of the model fixed effects and their 95% confidence intervals using Tukey's method to adjust for multiple comparisons, using the lsmeans function of the lsmeans package (Lenth, 2016). The effects of WM capacity were followed up with correlations between verbal and spatial WMC and the change in performance relevant for that phase within groups. Statistical significance was accepted at $p < .05$.

3. Results

3.1. General task improvement

The analysis showed a significant effect of block on movement time indicating an improvement in speed from block 1 to block 8 ($\chi^2(1) = 29.85$, $p < .001$, Fig. 4). Movement time decreased for both the implicit group (Coef = 60.4, 95% CI [25.6, 95.2], $p < .001$) and the explicit group (Coef = 49.8, 95% CI [15.9, 83.7], $p < .001$). There was no effect of group, nor was there a significant interaction between group and block. Neither verbal nor visuospatial WM capacity were related to the changes in movement time. There was no change in either reaction time or accuracy as indicated by the absence of effect for block and group, and no significant interaction between group and block (Figs. 3 & 5).

3.2. Consolidation of general improvements

The results for reaction time show a significant effect of block ($\chi^2(1) = 4.05$, $p = .044$) indicating slower reaction times at the start of day 2 compared to the end of day 1 (Fig. 3). There was no effect of group and no significant interaction between group and block. The increase in reaction time was similar in the implicit group (Coef = -86.5, 95% CI [-215.0, 42.4]) and the explicit group (Coef = -45.9, 95% CI [-184.0, 92.5]). WM capacity was not related to the (lack of) consolidation of response times. Movement times were also slower at the start of day 2 compared to the end of day 1 ($\chi^2(1) = 13.85$, $p < .001$, Fig. 4). There was no effect for group, but there was a significant interaction between group and block ($\chi^2(1) = 3.95$, $p = .047$). The slower movement times were only apparent for the explicit group (Coef = -15.4, 95% CI [-25.7, -5.5], $p < .001$) and not for the implicit group (Coef = -5.6, 95% CI [-14.3, 3.0], $p = .083$).

In contrast, accuracy was better at the start of day 2 compared to the end of day 1 ($\chi^2(1) = 4.62$, $p = .032$, Fig. 4). There was no effect for group, nor were there any significant interactions. The implicit group showed an increase in accuracy of 2.1° (95% CI [-0.9, 5.0]) and the explicit group showed an increase of 1.2° (95% CI [-1.7, 4.0]). WM capacity was not related to the consolidation of accuracy.

3.3. Sequence specific improvement

The analysis did not reveal any indications of sequence specific learning for reaction time or movement time, as indicated by a lack of significant effects for block, group, and the interaction between block and group (Figs. 3 & 4). There were indications of sequence specific learning for accuracy (Fig. 5). That is, there was a near significant effect for block ($\chi^2(1) = 3.73$, $p = .053$), and a significant interaction between group and block ($\chi^2(1) = 4.18$, $p = .041$). Participants in the implicit group showed a decrease in

[2] NOTE: a square root transformation was compared to a log transformation. A square root transformation fitted the data to a normal distribution better than a log transformation

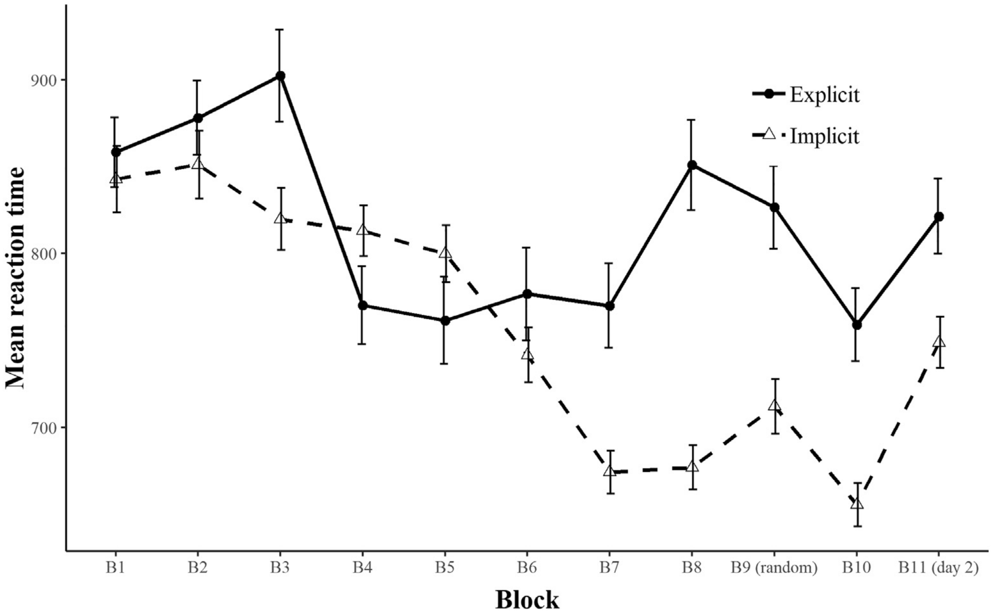

Fig. 3. Mean reaction times for blocks 1 through 11. Block 9 represents the random block and block 11 represents the first block of day 2. Error bars represent standard error.

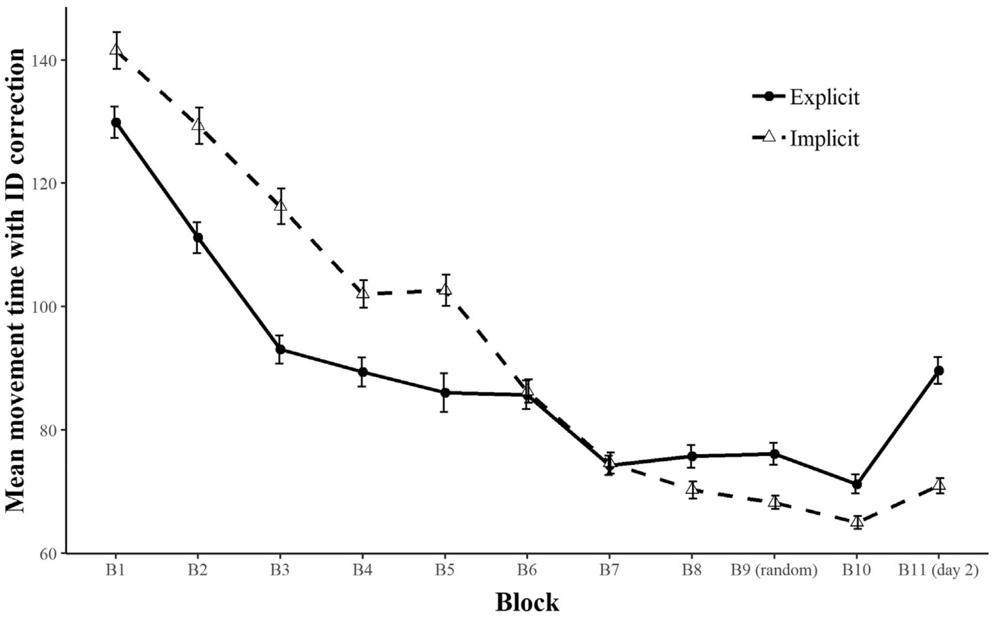

Fig. 4. Mean movement times (with ID correction) for blocks 1 through 11. Block 9 represents the random block and block 11 represents the first block of day 2. Error bars represent standard error.

accuracy in block 9 (Coef = −2.0, 95% CI [−4.4, 0.4], p = .015), which was not observed for the explicit group (Coef = −0.1, 95% CI [−2.5, 2.3], p = .91). There were no effects for either verbal or visuospatial WM capacity.

3.4. Consolidation of sequence specific improvements

There were no significant effects for condition or group, or the interaction between group and condition for reaction time and movement time, indicating no difference in performance between the learnt sequence and the new sequence (Figs. 6 & 7). For accuracy, there was only a significant effect of condition ($\chi^2(1)$ = 5.26, p = .022), with better accuracy in the learnt sequence compared to the new sequence for both the implicit group (Coef = −0.6, 95% CI [−2.5, 1.3]) and the explicit group (Coef = −1.5,

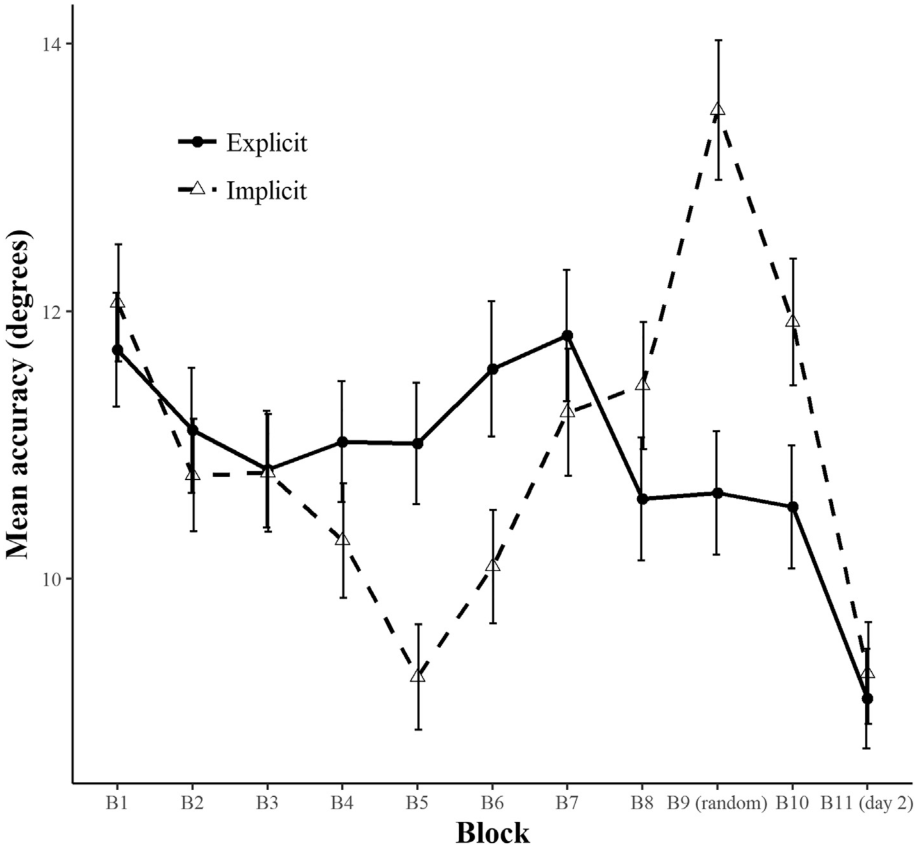

Fig. 5. Accuracy (in degrees) for blocks 1 through 11. Block 9 represents the random block and block 11 represents the first block of day 2. Error bars represent standard error.

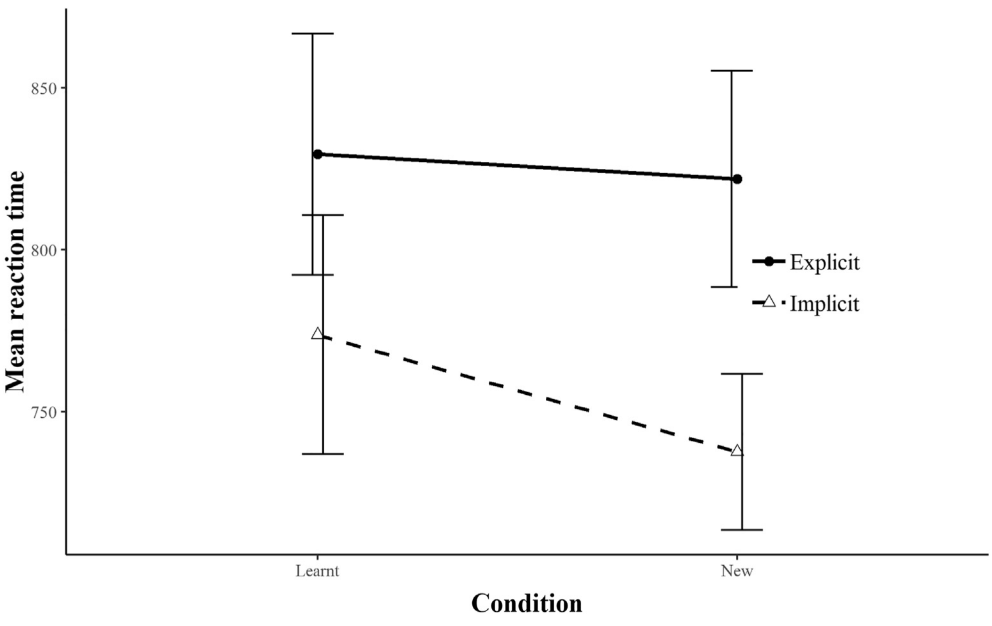

Fig. 6. Mean reaction times for trials representing the learnt sequence and the new sequence within block 12. Error bars represent standard error.

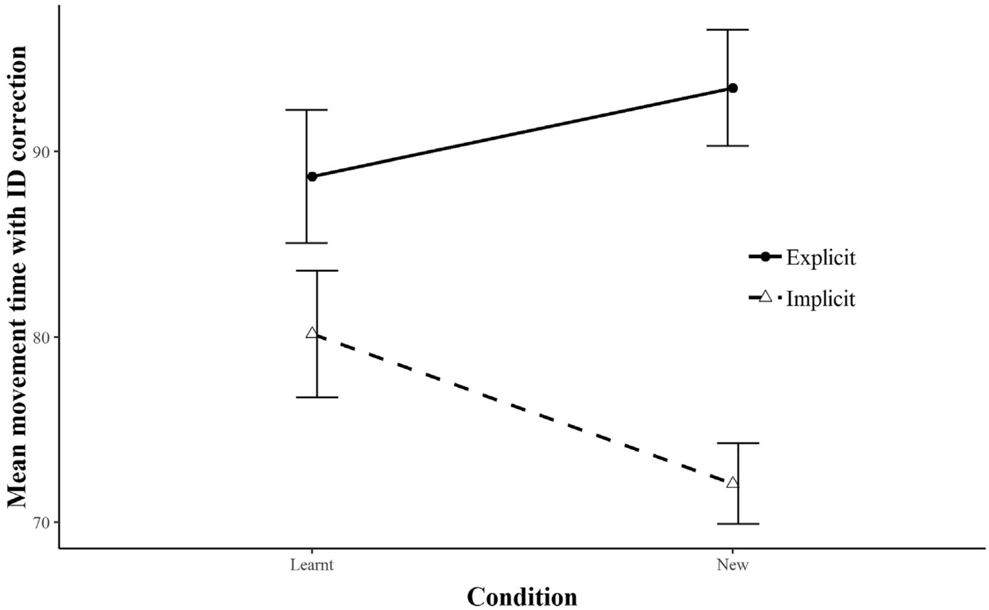

Fig. 7. Mean movement times (with ID correction) for trials representing the learnt sequence and the new sequence within block 12. Error bars represent standard error.

95% CI [−3.4, 0.3], (Fig. 8). There was no effect of WM capacity for either response time or accuracy.

3.5. Declarative knowledge

There was a significant effect of group on the number of triplets recalled ($\chi^2(2) = 4.09$, $p = .044$). The estimated number of triplets in the implicit group was 3.4 (95% CI [1.9, 6.0]) and in the explicit group 7.3 (95% CI [4.4, 12.1]). The estimated difference between the groups was 3.9 (95% CI [−11.5, 3.8]). Verbal and spatial WM capacity had no significant influence on the number of triplets reported. In the implicit group, 4 out of 12 children reported more than the chance level of 5 triplets, indicating some sequence awareness. In the explicit group this number was 9 out of 11. A Chi-Square test showed that more children in the explicit group showed sequence awareness compared to children in the implicit group ($\chi^2 = 5.49$, $p = .019$).

4. Discussion

This study investigated the role of WM capacity when motor sequences were learnt implicitly or explicitly by children. We advanced previous SRT studies by (a) adopting a task that measured movement accuracy in addition to both reaction time and movement time, (b) assessing whether performance improvements were related to general learning of the task or sequence specific learning, and (c) measuring whether learning had consolidated one day after practice. Results of day 1 showed that children from both groups (implicit and explicit) learnt to perform the task faster with practice, as evidenced by a decrease in movement time. However, these improvements were only revealed in general task improvements rather than sequence-specific improvements. There were indications that the implicit group, but not the explicit group, acquired the sequence, based on movement accuracy data. Significantly, both general and sequence specific improvements in movement accuracy consolidated for both groups by day 2, whereas improvements in reaction time and movement time were not. Contrary to our main hypothesis, however, neither verbal nor visuospatial WM capacity were associated with task improvements.

4.1. Performance on day 1

Interesting results emerged on day 1. Children in both groups improved movement time but not reaction time or accuracy. However, there was no evidence for sequence learning based on reaction time or movement time, while there was evidence for sequence learning (for the implicit group only) based on accuracy. The complexity of the task appears to have led to a speed-accuracy trade-off, with children prioritizing accuracy over speed. Hence, improvements in speed were merely due to familiarization with the task and not due to an anticipation of the next trial. This general improvement in movement time but not reaction time is consistent with the study of Moisello et al. (2009). In their study, adult participants performed an SRT task consisting of arm-reaching movements. They also observed that movement time continuously decreased during practice, while this was not the case for reaction time. However, in their experiment sequence learning (as opposed to the general improvements) was only indicated by a difference in reaction times between the sequence trials and random trials after practice. This difference was not present in our study. This may

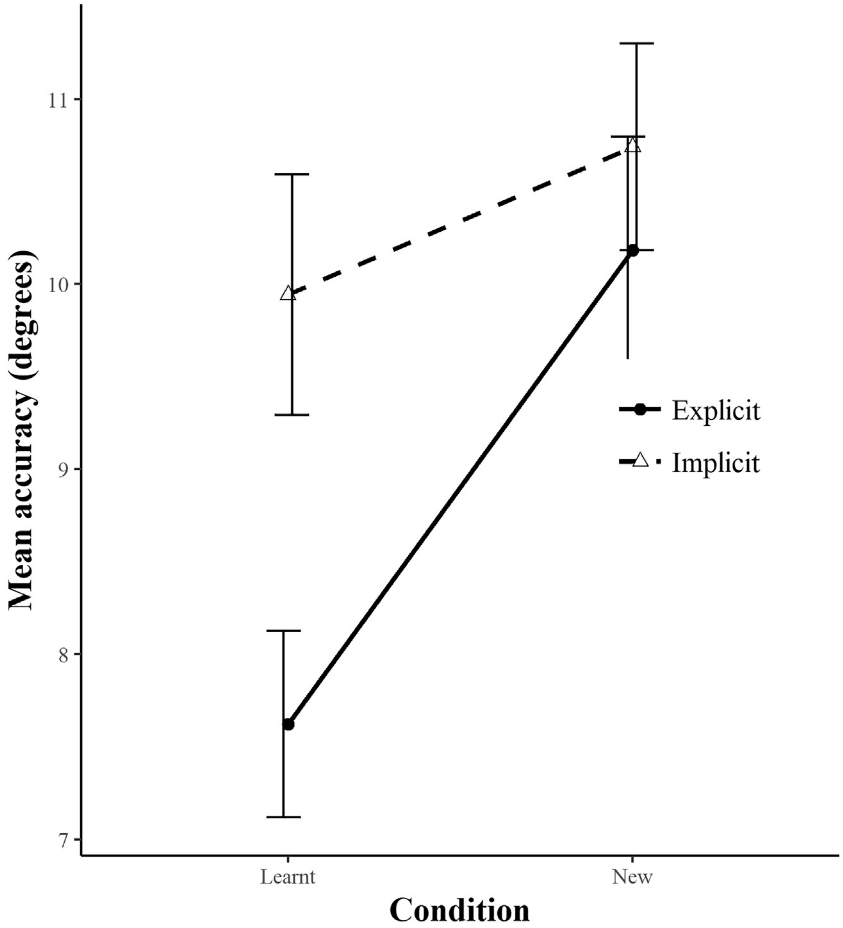

Fig. 8. Mean accuracy (in degrees) for trials representing the learnt sequence and the new sequence within block 12. Error bars represent standard error.

reflect a difference in learning between children and adults, a difference in task difficulty and/or be related to the larger amount of practice trials in the study of Moisello et al. (2009). Conversely, the implicit group's decline in accuracy when a new sequence was presented (block 9) might indicate that these children had learnt at least some of the sequence. This implies that in this complex task the spatial elements of the sequence were being learnt before the temporal elements.

We suspect that there was evidence for sequence learning in the implicit group but not the explicit group, possibly reflecting a difference in the speed-accuracy trade-off between groups (see Fitts, 1954, and Dayan & Cohen, 2011, for more discussion on speed-accuracy trade-off during early learning; see Lefebvre, Dricot, Gradkowski, Laloux, & Vandermeeren, 2012, for different speed-accuracy trade-off profiles in learning). Children in the implicit group displayed greatest improvements in accuracy during the initial blocks of practice (see Fig. 4). This indicates that children in the implicit group might have prioritized accuracy over speed, which may have been emphasized by the accuracy feedback after every trial. The improvements in movements speed may be solely a by-product of familiarization. Children in the explicit group showed minimal changes in accuracy, which suggests that these children were less concerned with being correct. Because children in the explicit group were provided with the sequence on the computer screen prior to every block, they may have focussed their attention on trying to recognize the sequence as it appeared on the screen. This would likely result in the categorization of responses, therein leading to minimal sequence learning in both speed and accuracy.

A noteworthy observation of performance on day 1 was the lack of difference between the implicit and explicit groups with regards to general task improvements. This is consistent with previous SRT studies that showed no differences between implicit and explicit training groups in the amount of improvement in response speed (Jongbloed-Pereboom et al., 2017; Thomas & Nelson, 2001). This suggests that children can improve general motor performance on an SRT task with and without receiving explicit instructions about the fixed sequence (Meulemans et al., 1998; Nemeth, Janacsek, & Fiser, 2013). We suggest that it shows that children habituate to the task constraints rather than the sequence.

4.2. Consolidation of learning

On day 2, children in both groups displayed slower reaction times, whereas slower movement times were most apparent in the explicit group. In addition, there was still no evidence of sequence specific learning for either movement time or reaction time. This strengthens the argument that day 1 improvements in movement speed primarily reflect general familiarization with the task. Accuracy, however, was better for both groups on day 2 compared to the final block of day 1. Moreover, when sequence-specific learning was assessed, children from both groups demonstrated better accuracy for the learnt sequence compared to the new sequence. This further strengthens the suggestion that in this complex sequence task movement accuracy was learnt before movement speed or anticipation. The sequence specific consolidation of accuracy suggests that the motor system can benefit from the continuous practice of a sequence of movements. It also raises the question as to whether this sequence specific consolidation of accuracy was related to an implicit or explicit learning process, or is perhaps underpinned by an improvement in proprioception.

Several studies have investigated consolidation in classic SRT tasks in children and there is general agreement that explicit task elements are consolidated better than implicit task elements (Ashworth, Hill, Karmiloff-Smith, & Dimitriou, 2014; Fischer, Wilhelm, & Born, 2007; Sugawara et al., 2014). In our experiment, feedback regarding movement accuracy was provided after every trial for both groups, and this might have elicited an explicit, trial-and-error learning process (for a discussion of why trial and error can lead to explicit learning, see Maxwell, Masters, Kerr, & Weedon, 2001). In contrast, research has also suggested that children may depend more on implicit learning (Nemeth et al., 2013), especially since the cognitive capacities needed for explicit learning are still developing (Masters et al., 2013). In the present experiment the lack of relations with WM capacity and a lesser degree of sequence knowledge in the implicit group (see sections below) corroborate the suggestion that movement accuracy was learnt implicitly. Possibly, the two processes, implicit and explicit learning, were involved in parallel (see Willingham, Nissen, & Bullemer, 1989) making it difficult to dissociate between the two.

4.3. *Sequence knowledge*

It was clear that the children in the explicit group could report more elements belonging to the sequence than children in the implicit group. However, none of the previously discussed results show clear indications of an explicit learning process within the explicit group and there were only minimal differences in performance and learning between both groups. This highlights that only gauging the amount of declarative knowledge at the end of the experiment is not a reliable method to determine if participants learnt the task implicitly or explicitly. We showed that children did build up sequence knowledge but they did not show any indication of using this knowledge to improve their performance. This was evidenced by the lack of anticipation which would be represented by a decrease in reaction time, a lack of sequence specific performance changes in the explicit group on day 1 and similar consolidation as participants in the implicit group on day 2. This finding is in accordance with Thomas and Nelson (2001) who showed that, on a group level, children who were pre-exposed to the sequence did not show better sequence specific learning compared to children who were not exposed to the sequence. They also found that some children had no awareness of the sequence despite being explicitly informed what the sequence was, whilst other children did demonstrate awareness of the sequence despite not being explicitly informed of the sequence. This highlights the large degree of individual variation in response to the manipulation (implicit or explicit paradigm). While we expected that WM capacity might explain some of this variation, our results did not confirm this hypothesis.

4.4. *Role of WM capacity on performance and learning*

There was also no evidence that verbal or visuospatial WM capacity influenced sequence specific improvements or general task improvements, nor the consolidation of these improvements, in either group. It was expected that verbal WM capacity would be related to sequence-specific learning in the explicit group (Buszard et al., 2017; Buszard & Masters, 2017). However, our results are consistent with the only other study looking into the role of WM capacity in an SRT task in children who showed that visuospatial WM capacity was not related to improvements in performance in both an implicit and explicit sequence learning group (Jongbloed-Pereboom et al., 2017). Several studies on implicit and explicit motor learning in sport related tasks also failed to show a role for WM capacity (Brocken, Kal, & van der Kamp, 2016; Krajenbrink, van Abswoude, Vermeulen, van Cappellen, & Steenbergen, 2018), or only found an effect on performance and not on learning (van Abswoude et al., 2018). This raises the question whether this indicates that children learn independent of working memory capacity regardless of the learning condition that is created (e.g. van Abswoude et al., 2018), whether the learning condition does not put enough load on WM capacity (e.g. Brocken et al., 2016), or whether the learning processes differ between children and adults. It needs to be acknowledged that the type of task used, in our case a span task, can also influence the results that are found (see Janacsek & Nemeth, 2013, for an elaborate discussion). Nevertheless, for the current experiment, we deemed the learning in both groups to be largely implicit given the minimal differences in learning between the groups, the lack of indication that children in the explicit groups used their acquired sequence knowledge and the lack of relations with WM capacity.

5. Conclusion

In this study we showed differential effects for children's sequence specific improvements in reaction time, movement time and accuracy. That is, during practice we only showed sequence specific changes in performance for accuracy in the implicit group. We also showed that accuracy was better consolidated the following day compared to reaction time and movement time, indicating both general learning and sequence learning. Including these three dependent variables goes beyond previous studies that have primarily measured response time in isolation. Furthermore, neither verbal nor visuospatial WM capacity were related to changes in performance or learning. Also, the knowledge that children acquired in the explicit group did not seem to be used during task performance.

We do need to acknowledge that, even though our sample size was based on previous work, the power to detect differences between groups and to detect a role for WM capacity is relatively small. As a result, we are cautious in generalizing our results outside of the current sample. Nevertheless, the contrasting findings between speed and accuracy highlights that different processes may play a role in learning and consolidation of different motor learning components in children.

To advance the field, our results suggest several avenues for further study. First, our findings need to be replicated using a larger sample. Not only would that show the robustness of the current findings, it would also make it possible to zoom in on individual differences regarding speed-accuracy trade-off profiles (see Lefebvre et al., 2006) and the role of the acquired sequence knowledge (see Thomas & Nelson, 2001). Second, further scrutiny of the differences between children and adults in this type of task is important in order to provide insight into age-related changes in the learning process. These steps are essential to further unravel the processes and mechanisms related to implicit and explicit motor sequence learning in children.

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Declaration of Competing Interest

None.

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Appendix A. Instructions given to the participant at the start of day 1 and day 2 of the experiment for each group

Instructions appearing on the computer screen on day one in the explicit group

- Welcome. We are going to play a game. Are you ready?
  (experimenter explains the game)
- Lets practice first
  (child performs F1)
- Well done! Your fasters correct time is now on the scoreboard
- Lets practice one last time. Goal = go as fast as you can… but you need to be correct!
  (child performs F1 again)
- Great! Your fastest correct time is now on the scoreboard
  (experimenter explains presence of the sequence)
- The order is: 10, 50, 70, 30, 50, 10, 70, 30, 10, 70. If you remember this order it will help you go faster
- Lets see how fast you can be! But we only count it if the green light comes on
  (child performs the experiment)

Between blocks children see: Good job! Your fastest correct time is now on the scoreboard. Remember, the numbers appear in the same order most of the time. 10, 50, 70, 30, 50, 10, 70, 30, 10, 70.

Instructions appearing on the computer screen on day one in the explicit group

- Welcome. We are going to play a game. Are you ready?
  (experimenter explains the game)
- Lets practice first
  (child performs F1)
- Well done! Your fasters correct time is now on the scoreboard
- Lets practice one last time. Goal = go as fast as you can… but you need to be correct!
  (child performs F1 again)
- Great! Your fastest correct time is now on the scoreboard
  (experimenter explains that game will start now)
- Lets see how fast you can be! But we only count it if the green light comes on
  (child performs the experiment)

Between blocks children see: Good job! Your fastest correct time is now on the scoreboard.

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